



RESEARCH MEMORANDUM

INVESTIGATION OF EFFECTS OF REYNOLDS NUMBER ON
OVER-ALL PERFORMANCE OF AN EIGHT-STAGE
AXIAL-FLOW RESEARCH COMPRESSOR WITH
TWO TRANSONIC INLET STAGES

By Richard P. Geye and James G. Lucas

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

WASHINGTON
February 15, 1957
Declassified July 28, 1960

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INVESTIGATION OF EFFECTS OF REYNOLDS NUMBER ON OVER-ALL PERFORMANCE
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SUMMARY

The effect of Reynolds number on the performance of an eight-stage axial-flow compressor with transonic inlet stages was investigated at an inlet-air temperature of approximately 410° R (-50° F) with the compressor uninsulated for a range of equivalent weight flow at 90 and 100 percent of equivalent design speed and at single flow points at 80-percent speed for chord Reynolds numbers from 96,000 to 1,080,000. At design speed the peak adiabatic efficiency decreased from 0.834 to 0.730, the maximum equivalent weight flow from 72.1 to 60.5 pounds per second, and the surge pressure ratio from 10.7 to 8.8 as the chord Reynolds number was decreased from 1,050,000 to 96,000. At 90-percent speed the efficiency decreased from 0.839 to 0.720, the weight flow from 62.4 to 50.8 pounds per second, and the pressure ratio from 8.2 to 6.2 as the chord Reynolds number was decreased from 1,050,000 to 112,000. Equivalent weight flow also decreased as chord Reynolds number was decreased at 80-percent speed, and rotating stall was encountered at approximately the same equivalent weight flow as it had been at 73-percent speed at a high chord Reynolds number (1,100,000). Thus, rotating stall was encountered at higher equivalent compressor speeds as chord Reynolds number was decreased.

The effects of heat transfer were investigated by operating the compressor at an inlet-air temperature of 410° R with the compressor insulated and at 550° R with the compressor uninsulated and comparing these data with those at 410° R with the compressor uninsulated. The effect of insulation with the low inlet temperature on Reynolds number effect was small, indicating that the data for low inlet temperature (uninsulated) provide a reasonably accurate measure of the change in compressor performance with Reynolds number. Increasing the inlet temperature from 410° to 550° R with the compressor uninsulated partially masks the effects of Reynolds number on adiabatic efficiency.

INTRODUCTION

One of the major limitations on flight at extremely high altitudes with turbojet powerplants is the detrimental effect of low Reynolds numbers on component performance. One of the components most adversely affected is the compressor. Previous investigations (refs. 1 and 2) have been concerned with the effects of Reynolds number on compressors designed for subsonic velocities relative to the blade rows and conservative stage pressure ratios.

To facilitate the study of the performance problems of multistage compressors with high-pressure-ratio, high Mach number stages, an eight-stage axial-flow compressor having two transonic inlet stages was designed, fabricated, and tested at the NACA Lewis laboratory. Reference 3 presents a detailed account of the aerodynamic design and over-all performance data of this compressor. During the course of this study of performance problems, several modifications were incorporated in the compressor in an attempt to improve the mechanical characteristics of the blading and the aerodynamic performance at high speeds. These modifications are presented in reference 4, and the compressor performance obtained with these modifications is presented in references 5 and 6.

In order to determine the effect of Reynolds number on the performance of this modified eight-stage compressor, the over-all performance characteristics of the compressor were obtained at 80, 90, and 100 percent of equivalent design speed for a series of inlet-air pressures ranging from 12.9 to 0.9 inch of mercury absolute. This report presents the over-all performance characteristics for this range of pressures. In addition, the effects of heat transfer are evaluated by obtaining the compressor performance with and without casing insulation at an inlet-air temperature of 410° R and without casing insulation at an inlet-air temperature of 550° R.

SYMBOLS

- c chord length at tip of first rotor, ft
- P absolute total pressure, in. Hg
- Re Reynolds number relative to first rotor tip, $\rho V' c / \mu$
- T total temperature, $^{\circ}$ R
- V' velocity relative to first rotor tip, ft/sec
- w weight flow, lb/sec

- δ ratio of inlet total pressure to NACA standard sea-level pressure of 29.92 in. Hg abs
- η adiabatic temperature-rise efficiency
- θ ratio of inlet total temperature to NACA standard sea-level temperature of 518.7° R
- μ viscosity based on total temperature at tip of first rotor, lb/(ft)(sec)
- ρ static density at tip of first rotor, lb/cu ft

Subscripts:

- 0 inlet depression-tank station
- 20 discharge measuring station

APPARATUS AND INSTRUMENTATION

Compressor

A cross-sectional view of the compressor, the inlet bellmouth nozzle, and the discharge collector is shown in figure 1. The aerodynamic design details for this compressor are presented in references 3 and 4; and the over-all performance (high Reynolds number), rotating stall, and blade-vibration characteristics are presented in references 5 and 6. The major design values are as follows:

Total-pressure ratio	10.26
Equivalent weight flow, lb/sec	72.4
Equivalent tip speed, ft/sec	1218
Inlet hub-tip diameter ratio	0.46
Diameter at inlet to first rotor, in.	20.86
Chord at tip of first rotor, ft	0.3147

Installation

The compressor was driven by a 15,000-horsepower variable-frequency electric motor. The speed was maintained constant by an electronic control and was measured by an electric chronometric tachometer. Air entered the compressor through a submerged thin-plate orifice, a butterfly inlet throttle for controlling inlet pressure, and a depression tank 6 feet in diameter and approximately 10 feet long. Screens in the depression tank and a bellmouth faired into the compressor inlet were used to

obtain a uniform distribution of air entering the compressor. Air was discharged from the compressor into a collector connected to the laboratory altitude exhaust system. Air weight flow was controlled by a butterfly valve located in the exhaust ducting.

Instrumentation

The axial locations of the instrument measuring stations are shown in figure 1. The inlet depression-tank station and the compressor discharge station had axial locations that were in accordance with reference 7. The radial distribution of outlet total temperature was obtained from multiple-probe rakes located at the area centers of equal annular areas. The discharge static pressure was obtained from six wall static taps. The instruments used at each station are similar to those illustrated in reference 5. The methods of measurement were as follows:

- (1) Temperature measurement: self-balancing potentiometers
- (2) Pressure measurement: mercury manometers referenced to atmosphere for inlet pressures greater than 3 inches of mercury absolute, dibutylphthalate manometers referenced to pressure measured with a 0 to 100-millimeter pressure gage for inlet pressures less than 3 inches of mercury absolute, and mercury manometers referenced to atmosphere for all compressor discharge pressures
- (3) Weight-flow measurement: a thin-plate submerged orifice that was changed depending on inlet volume flow so that the pressure drop across the orifice was generally maintained between 20 and 80 inches of water

PROCEDURE

The investigation of the effect of Reynolds number and heat transfer on the over-all compressor performance was carried out in three phases:

- (1) The compressor was uninsulated, an inlet-air temperature of approximately 410° R (-50° F) was maintained, and the Reynolds number relative to the tip of the first rotor was varied from approximately 96,000 to 1,080,000 by controlling the inlet-air pressure. The Reynolds number used in this report is defined as $\rho V' c / \mu$, where ρ is the static density, V' is the relative velocity, μ is the viscosity based on total temperature, and c is the chord length at the tip of the first rotor. During this phase the compressor was operated at 80, 90, and 100 percent of equivalent design speed. At 90 and 100 percent of design speed at each inlet pressure, a range of airflows was investigated from a maximum flow at which the compressor discharge piping system was choked to a

minimum flow at which surge occurred. At each inlet pressure at 80 percent of design speed a single data point was obtained, the maximum flow at which rotating stall was encountered.

(2) The compressor was insulated with 4 inches of Fiberglas, an inlet temperature of approximately 410° R (-50° F) was maintained, and the Reynolds number relative to the tip of the first rotor was varied from approximately 96,000 to 1,030,000 by controlling inlet pressure. The compressor was operated at 100 percent of equivalent design speed, a range of airflows being investigated at each inlet pressure.

(3) The compressor was uninsulated, an inlet temperature of approximately 550° R (90° F) was maintained, and the performance of the compressor was determined at Reynolds numbers relative to the tip of the first rotor of approximately 100,000 and 150,000. In this phase the compressor was operated at only 90 percent of equivalent design speed because of compressor discharge temperature limitations.

Table I summarizes conditions at which data were obtained. The over-all compressor performance characteristics were calculated from the orifice and drive-motor speed measurements, the inlet total pressure and temperature, and the discharge static pressure and total temperature. The discharge total pressure was calculated by the procedure recommended in reference 7. This method does not credit the compressor with nonuniformities of outlet flow velocity or deviation from axial discharge and is the same as the method used in the presentation of the calculated over-all performance data in references 5 and 6.

RESULTS AND DISCUSSION

Compressor Performance

High Reynolds number. - The over-all performance characteristics of the compressor were obtained with the Reynolds number relative to the tip of the first rotor maintained at approximately 1,100,000. (At design-point conditions the ratios of Reynolds number at the first-rotor hub and the first-stator hub and tip to Reynolds number at the first-rotor tip are 0.48, 0.30, and 0.27, respectively.) These performance characteristics are presented in figure 2, the data of which were obtained from reference 6. The over-all total-pressure ratio is plotted as a function of equivalent weight flow at various values of equivalent speed, with contours of constant adiabatic temperature-rise efficiency, the surge-limit line, and the rotating-stall region indicated. This performance is discussed in detail in reference 6.

Variation with inlet pressure. - The variation of compressor over-all total-pressure ratio with equivalent weight flow is shown in figure 3(a) for compressor speeds of 80, 90, and 100 percent of equivalent design speed (13,380 rpm), an inlet-air temperature of 410° R, and inlet-air pressures ranging from 12.9 to 0.9 inch of mercury absolute. The

surge limit and the region in which rotating stall was encountered at a high Reynolds number (ref. 6) are also indicated. The variation of adiabatic temperature-rise efficiency with over-all total-pressure ratio is shown in figure 3(b) for 100 and 90 percent of equivalent design speed.

Effect of Reynolds Number on Compressor Performance

In order to make the following discussion readily interpreted on the basis of altitude, figure 4 presents a plot of altitude against the compressor Reynolds number used in the present investigation for equivalent compressor speeds of 90 and 100 percent of design and flight Mach numbers of 0.8 and 1.5. The Reynolds number used in figure 4 is based on measured data and takes into account the variation of equivalent weight flow. A pressure-recovery factor of 100 percent is assumed in the calculation.

Adiabatic efficiency. - The variation of peak adiabatic efficiency with Reynolds number, which was obtained at an inlet temperature of 410° R with the compressor uninsulated, is presented in figure 5(a) for 100 percent of equivalent design speed and in figure 5(b) for 90 percent of equivalent design speed. At design speed the peak adiabatic efficiency decreases from 0.834 at a Reynolds number of 1,050,000 to 0.798 at a Reynolds number of 250,000 and to 0.730 at a Reynolds number of 96,000. At 90 percent of equivalent design speed the loss in efficiency follows a similar trend, the peak adiabatic efficiency decreasing from 0.839 at a Reynolds number of 1,050,000 to 0.794 at a Reynolds number of 250,000 and to 0.720 at a Reynolds number of 112,000.

For turbulent-boundary-layer flow over a flat plate, the losses are approximately proportional to Reynolds number to the $-1/5$ power. It is therefore suggested that it may be more than numerical coincidence that, using the efficiencies presented in figure 5, the minimum loss as represented by $(1 - \eta)$ is approximately proportional to $Re^{-1/5}$. However, without data from compressors of greatly different physical and aerodynamic geometry, it is not possible to demonstrate that this fact has any real physical significance.

Equivalent weight flow. - The maximum equivalent weight flow obtained at an inlet temperature of 410° R with the compressor uninsulated is plotted as a function of Reynolds number for 90 and 100 percent of equivalent design speed in figure 6. At design speed the maximum equivalent weight flow decreases gradually from 72.1 to 69.1 pounds per second as the Reynolds number is decreased from 1,050,000 to 250,000. As the Reynolds number is decreased to 96,000, the equivalent weight flow decreases rapidly to 60.5 pounds per second. At 90 percent of equivalent design speed the maximum equivalent weight flow decreases similarly, from 62.4 pounds per second at a Reynolds number of 1,050,000 to 58.7 pounds per second at a Reynolds number of 250,000 and to 50.8 pounds per second at a Reynolds number of 112,000.

Surge limit. - The variation of surge pressure ratio with Reynolds number is plotted in figure 7 at an inlet temperature of 410° R with the compressor uninsulated. The design-speed surge pressure ratio decreases from 10.7 at a Reynolds number of 1,050,000 to 9.9 at a Reynolds number of 250,000 and to 8.8 at a Reynolds number of 100,000. Similarly, the surge pressure ratio at 90 percent of equivalent design speed decreases from 8.2 at a Reynolds number of 1,050,000 to 7.4 at a Reynolds number of 250,000 and to 6.2 at a Reynolds number of 112,000. In figure 3(a) it can be seen that the surge points obtained at the various Reynolds numbers (inlet pressures) at 90 and 100 percent of equivalent design speed approximately coincide with the surge-limit line defined by the 80-, 90-, and 100-percent-speed surge points obtained at a Reynolds number of 1,100,000 (ref. 6). Thus, it appears that the decrease in surge pressure ratio and equivalent weight flow with decreasing Reynolds number is such that the surge limit obtained at a high Reynolds number can be used to roughly approximate the surge limit that can be expected at low Reynolds numbers.

Rotating stall. - In figure 3(a) single data points obtained at 80 percent of equivalent design speed at four inlet pressures are presented. These points represent the highest equivalent weight flows at which rotating stall was encountered at the various inlet pressures at 80 percent of design speed. These data approximate the first-stage stall line obtained between 70 and 73 percent of equivalent design speed at a Reynolds number of 1,100,000 in reference 6. Thus, the equivalent weight flow at which rotating stall is encountered appears to remain approximately constant regardless of the value of Reynolds number. However, since there is a decrease in equivalent weight flow at a given equivalent speed as Reynolds number is decreased, rotating stall is encountered at progressively higher equivalent speeds as Reynolds number is decreased.

Effect of Heat Transfer on Indicated Performance

In order to determine the effect of heat transfer on the indicated effects of Reynolds number, additional data were obtained at an inlet-air temperature of 410° R with the compressor insulated and at an inlet-air temperature of 550° R with the compressor uninsulated. To simulate the case of no heat transfer, the compressor was insulated and the compressor performance was obtained at design speed with an inlet-air temperature of 410° R and inlet-air pressures ranging from 10.2 to 0.9 inch of mercury absolute. The variations of over-all total-pressure ratio with equivalent weight flow and of adiabatic temperature-rise efficiency with over-all total-pressure ratio obtained under these conditions are shown in figures 8(a) and (b), respectively.

To simulate the case of maximum heat transfer from compressor to atmosphere, the compressor was left uninsulated and the compressor performance was obtained at 90 percent of design speed with an inlet-air temperature of 550° R and inlet-air pressures of 2.2 and 1.5 inches of mercury absolute. For these conditions, the variation of over-all total-pressure ratio with equivalent weight flow is shown in figure 9(a) and

the variation of adiabatic temperature-rise efficiency with over-all total-pressure ratio is presented in figure 9(b). Because of compressor discharge temperature limitations, data at the high-inlet-temperature condition could not be obtained at 100 percent of equivalent design speed; therefore, the comparisons are to be made at 90-percent speed.

The compressor performance variables of peak efficiency, maximum equivalent weight flow, and surge pressure ratio for the conditions stated are compared with the previously discussed data obtained at an inlet temperature of 410° R with the compressor uninsulated in figures 10 to 12. The variation in indicated peak efficiency with Reynolds number at design speed (fig. 10(a)) is much the same for the two cases of insulated and uninsulated compressor with an inlet temperature of 410° R; however, the insulated-compressor indicated efficiency is about 1 point lower than that of the uninsulated at the highest Reynolds number and $2\frac{1}{2}$ points lower at the lowest Reynolds number. This indicates that the data obtained with the compressor uninsulated and an inlet temperature of 410° R are a fairly accurate representation of the effects of Reynolds number with no heat transfer. The temperature of the ambient air surrounding the compressor during all tests was about 560° R. Therefore, it can be assumed that, with the compressor uninsulated and an inlet temperature of 410° R, the amount of heat transfer into and out of the compressor was about equal. This could explain the relatively good agreement between the insulated and uninsulated data.

When the compressor was operated uninsulated and the inlet temperature increased to 550° R (about equal to the ambient temperature so that all heat transfer is from the compressor to the atmosphere), the effects of Reynolds number on compressor efficiency were partially masked (fig. 10(b)). Although data could only be obtained at low Reynolds numbers for this condition because of rig operational limits, the level and variation of efficiency with Reynolds number are markedly changed. At the lowest Reynolds number (approximately 1.0×10^5) the indicated peak compressor efficiency for the 550° R tests is about 7 points higher than that measured at an inlet temperature of 410° R. In addition, the indicated increase in efficiency at these low Reynolds numbers is about 2 points for a 50-percent increase in Reynolds number with an inlet temperature of 550° R as compared with 4 points for the same change in Reynolds number with an inlet temperature of 410° R.

In figures 11 and 12 it can be seen that heat transfer has little effect on the variation of maximum equivalent weight flow and surge pressure ratio with Reynolds number.

From the data presented herein it can be concluded that, with high-pressure-ratio compressors, the effects of heat transfer on equivalent weight flow and surge pressure ratio are relatively minor; however, the

effects of heat transfer on indicated adiabatic temperature-rise efficiency are extremely important in the evaluation of the effects of Reynolds number. For this reason, no Reynolds number investigation should be conducted without exercising a great deal of care to minimize heat transfer.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the effect of Reynolds number and heat transfer on the over-all performance of a modified eight-stage axial-flow compressor with two transonic inlet stages:

1. With the compressor uninsulated and an inlet temperature of 410° R, the design-speed peak adiabatic efficiency decreased from 0.834 at a Reynolds number of 1,050,000 to 0.730 at a Reynolds number of 96,000, and the 90-percent-speed peak adiabatic efficiency decreased from 0.839 at a Reynolds number of 1,050,000 to 0.720 at a Reynolds number of 112,000.
2. With the compressor uninsulated and an inlet temperature of 410° R, the maximum equivalent weight flow decreased from 72.1 to 60.5 pounds per second at design speed and from 62.4 to 50.8 pounds per second at 90-percent design speed for the range of Reynolds number covered.
3. With the compressor uninsulated and an inlet temperature of 410° R, the surge pressure ratio decreased from 10.7 to 8.8 at design speed and from 8.2 to 6.2 at 90 percent of design speed for the range of Reynolds number covered.
4. Rotating stall will be encountered at progressively higher equivalent compressor speeds as Reynolds number is decreased.
5. The effect on indicated performance at equivalent design speed of insulating the compressor with an inlet temperature of 410° R was to decrease the level of measured performances slightly but not to significantly change the variations in performance with Reynolds number obtained at the same inlet temperature with the compressor uninsulated.
6. An increase in inlet temperature from 410° to 550° R with the compressor uninsulated at 90-percent equivalent design speed partially masked the effects of Reynolds number on compressor adiabatic temperature-rise efficiency because of heat transfer from the compressor to the ambient test atmosphere.

REFERENCES

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2. Walker, Curtis L., Huntley, S. C., and Braithwaite, W. M.: Component and Over-All Performance Evaluation of an Axial-Flow Turbojet Engine over a Range of Engine-Inlet Reynolds Numbers. NACA RM E52B08, 1952.
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4. Geye, Richard P., and Voit, Charles H.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. IV - Modification of Aerodynamic Design and Prediction of Performance. NACA RM E55B28, 1955.
5. Standahar, Raymond M., and Geye, Richard P.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. V - Preliminary Analysis of Over-All Performance of Modified Compressor. NACA RM E55A03, 1955.
6. Standahar, Raymond M., Hanson, Morgan P., and Geye, Richard P.: Investigation of a High-Pressure-Ratio Eight-Stage Axial-Flow Research Compressor with Two Transonic Inlet Stages. VI - Over-All Performance, Rotating Stall, and Blade Vibration at Low and Intermediate Compressor Speeds. NACA RM E55I13, 1955.
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TABLE I. - SUMMARY OF TEST CONDITIONS¹

P_0 , in. Hg	Uninsulated, $T_0 = 410^\circ R$		Insulated, $T_0 = 410^\circ R$	Uninsulated, $T_0 = 550^\circ R$	
	Speed, percent design				
	100	90	80	100	90
12.9			▼		
11.1		○			
10.2	□			□	
8.2	◊	◊			
5.3	△	△			
3.2	△	△		△	
2.2	□	□	■	□	□
1.9				□	
1.8			●		
1.7			◆		
1.6	△			△	
1.5	◊	◊	■		◊
1.4		◊			
1.3	□			□	
1.1	□	□		□	
0.9	▼			▼	

¹Open and tailed symbols: data obtained over flow range from maximum to surge; solid symbols: data obtained only at maximum flow for rotating stall; tailed symbols: insulated compressor.

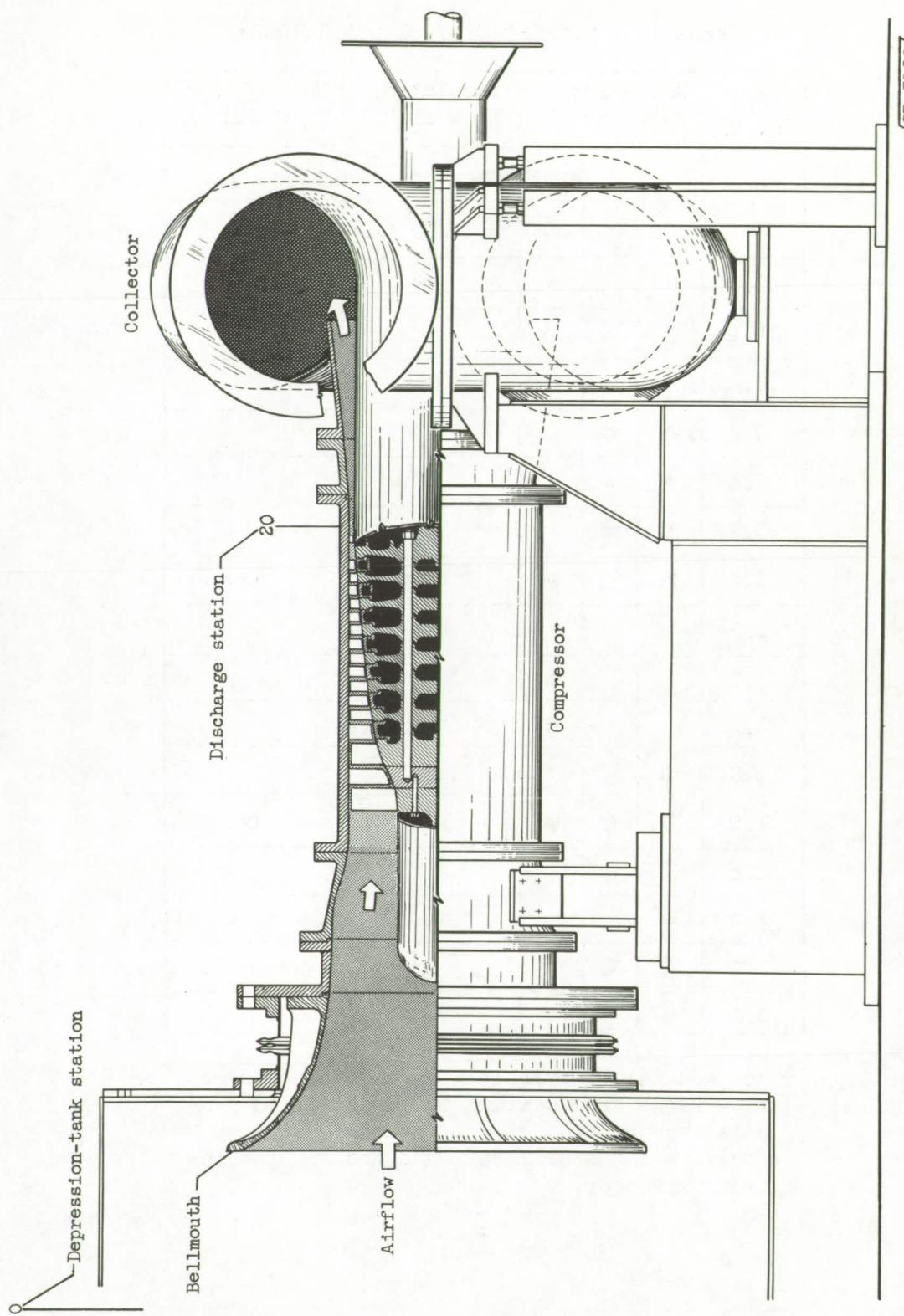


Figure 1. - Cross-sectional view of eight-stage axial-flow compressor, inlet bellmouth, and discharge collector.

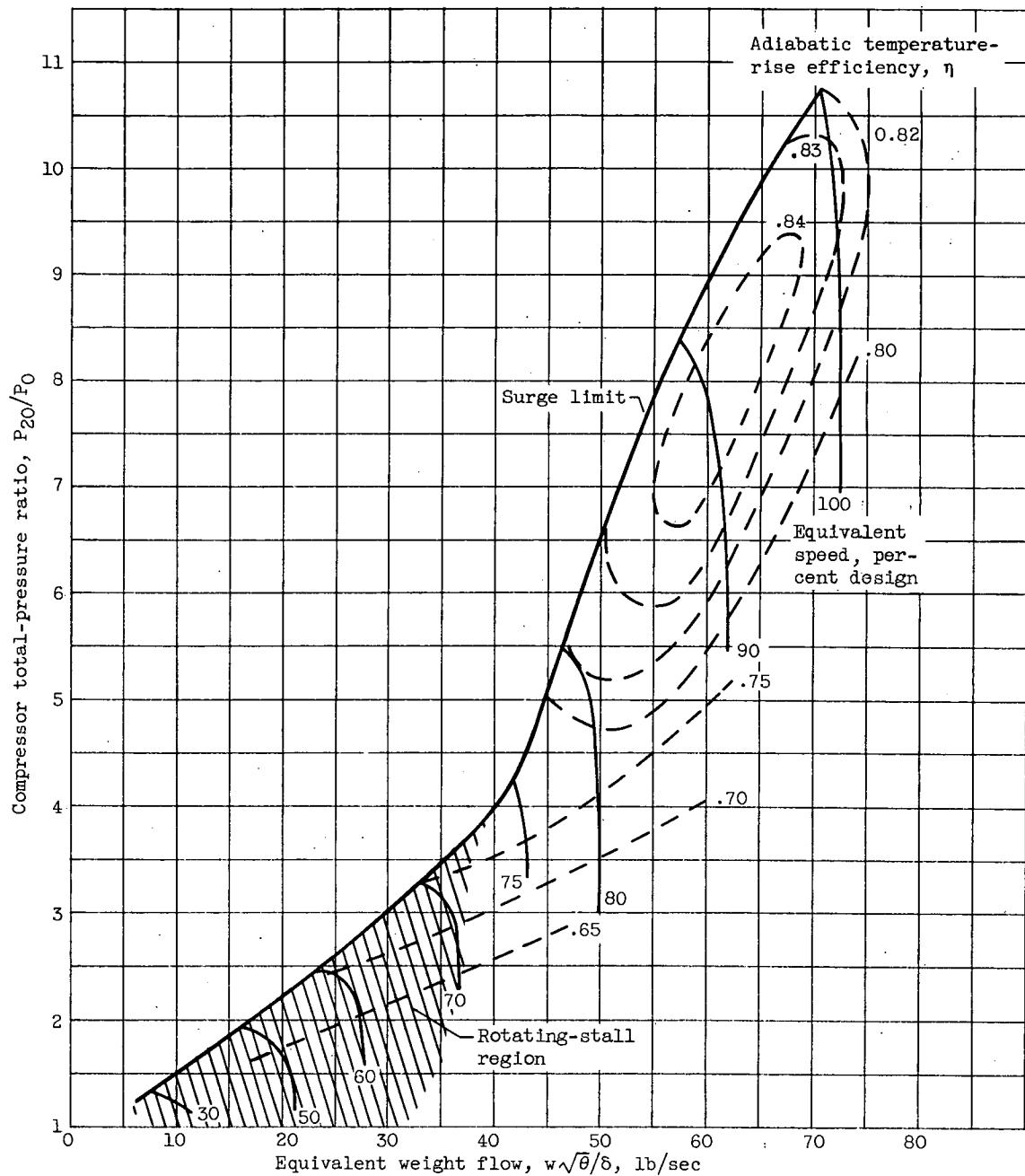
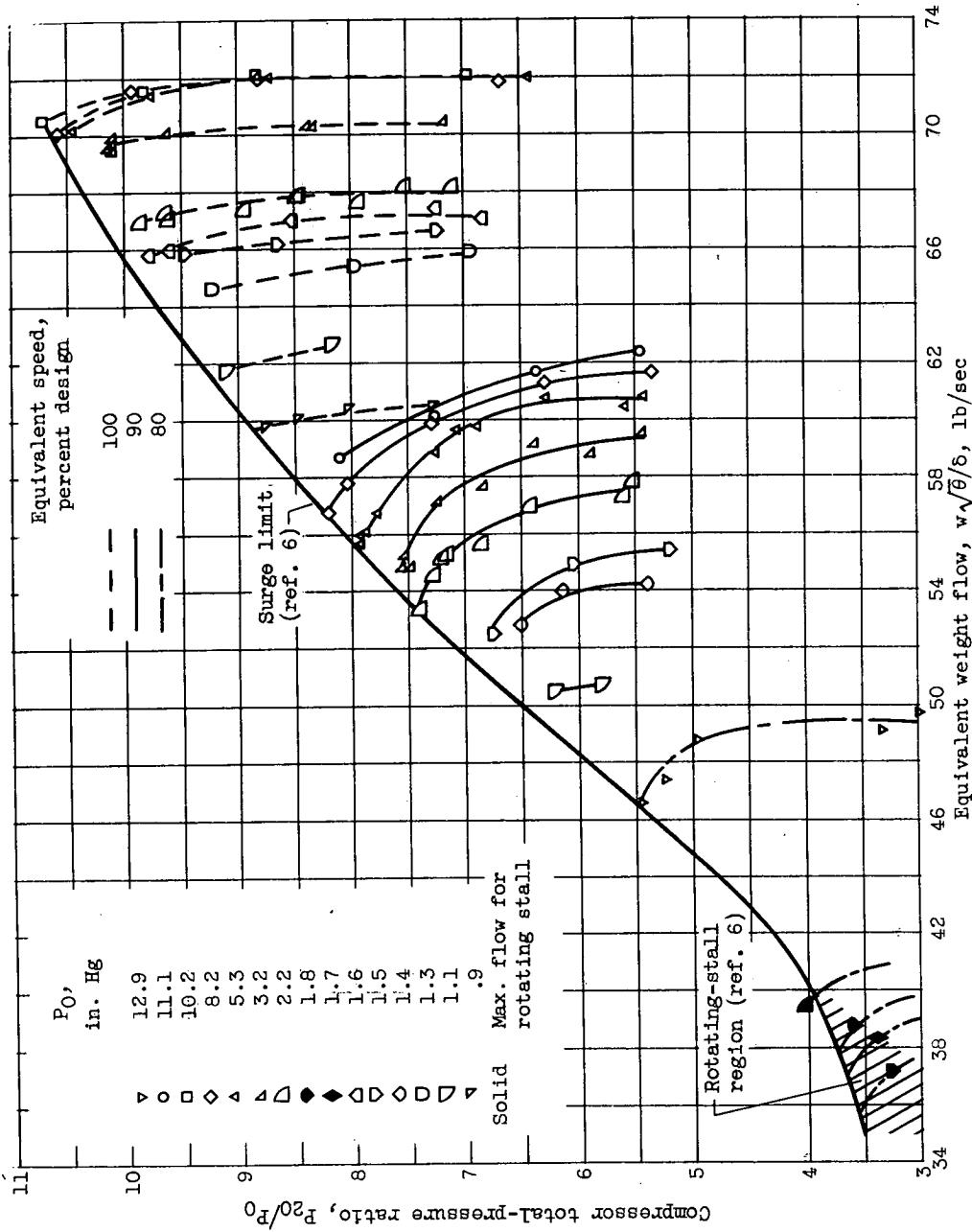
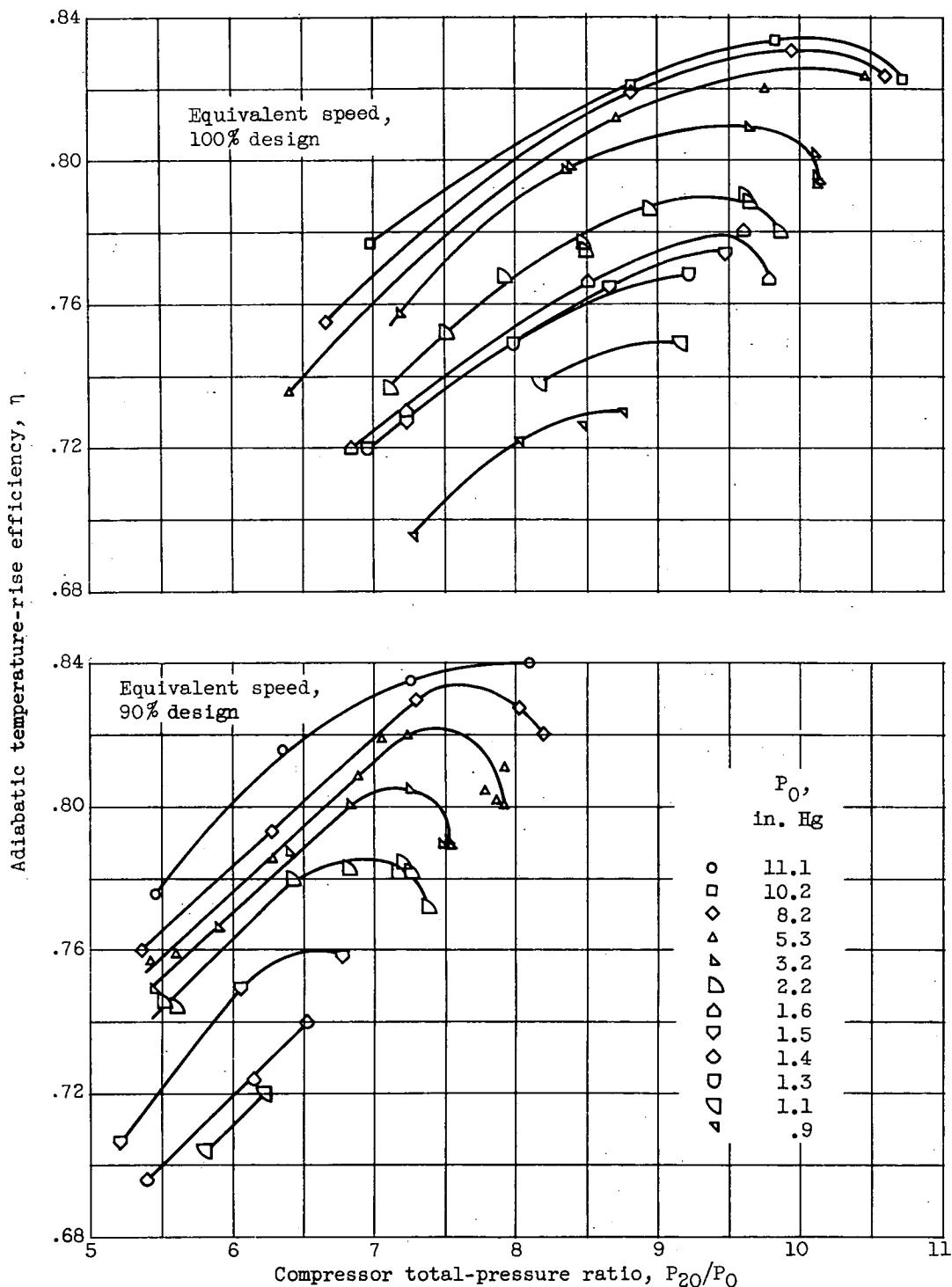


Figure 2. - Over-all performance characteristics of modified eight-stage axial-flow compressor at Reynolds number of 1,100,000 (ref. 6).



(a) Pressure-ratio and equivalent-weight-flow characteristics.
Figure 3. - Effect of inlet pressure on over-all performance. Inlet temperature, $410^\circ R$; compressor uninsulated.



(b) Efficiency and pressure-ratio characteristics.

Figure 3. - Concluded. Effect of inlet pressure on over-all performance.
Inlet temperature, 410° R; compressor uninsulated.

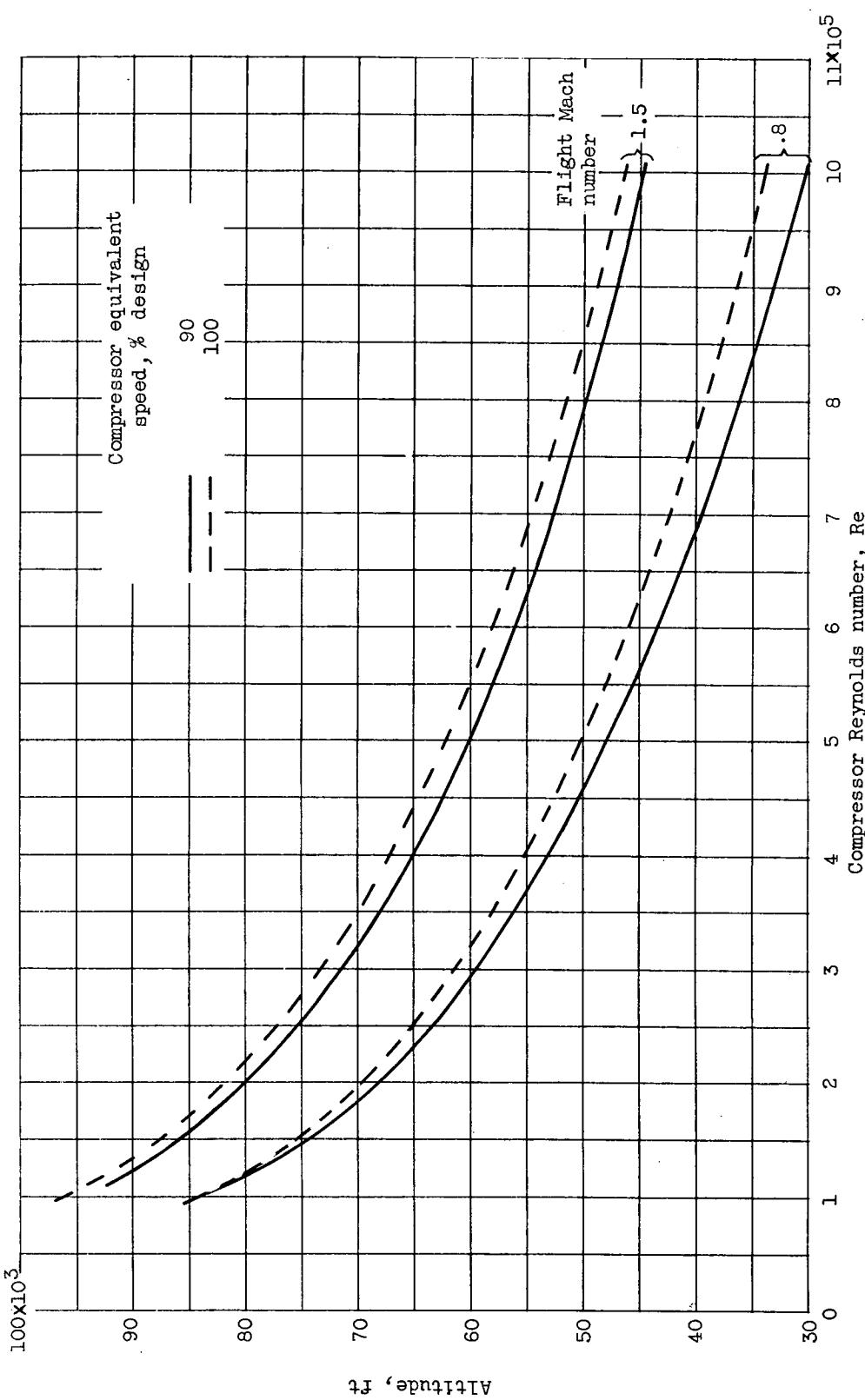


Figure 4. - Compressor Reynolds number as function of altitude for flight Mach numbers of 0.8 and 1.5.

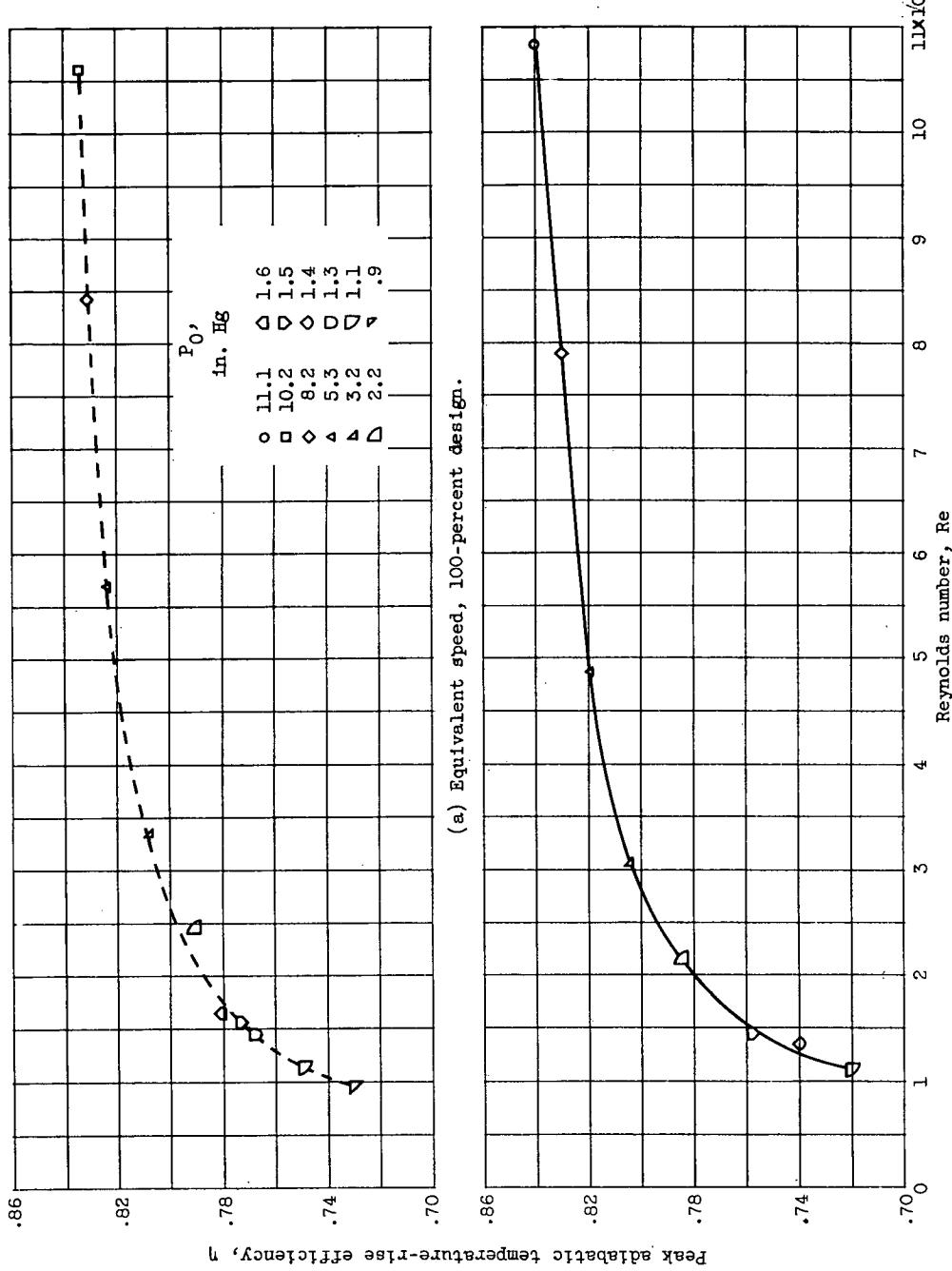


Figure 5. - Variation of peak efficiency with Reynolds number. Inlet temperature, $410^\circ R$; compressor uninsulated.

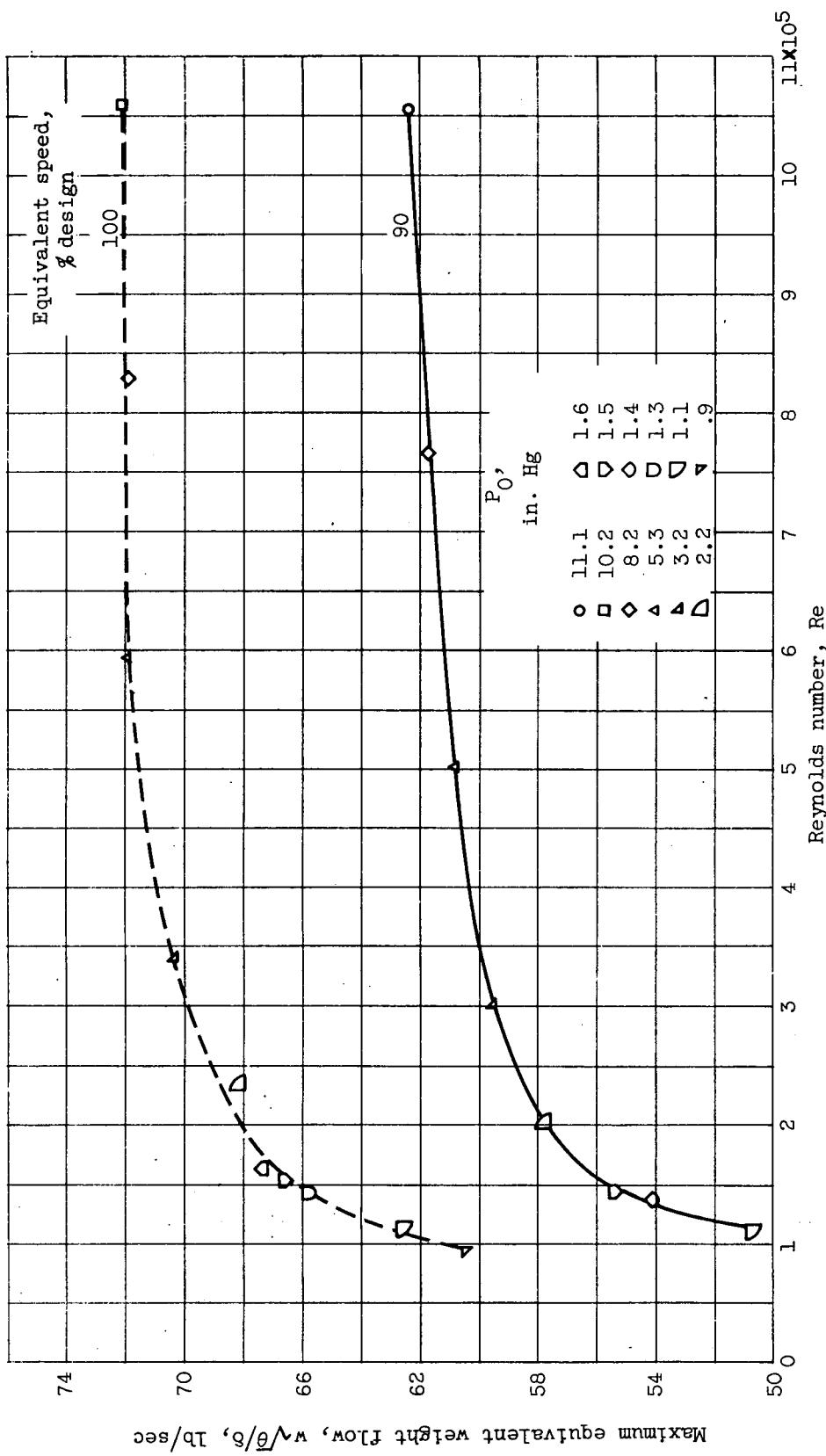


Figure 6. - Variation of maximum equivalent weight flow with Reynolds number. Inlet temperature, 410° R; compressor uninsulated.

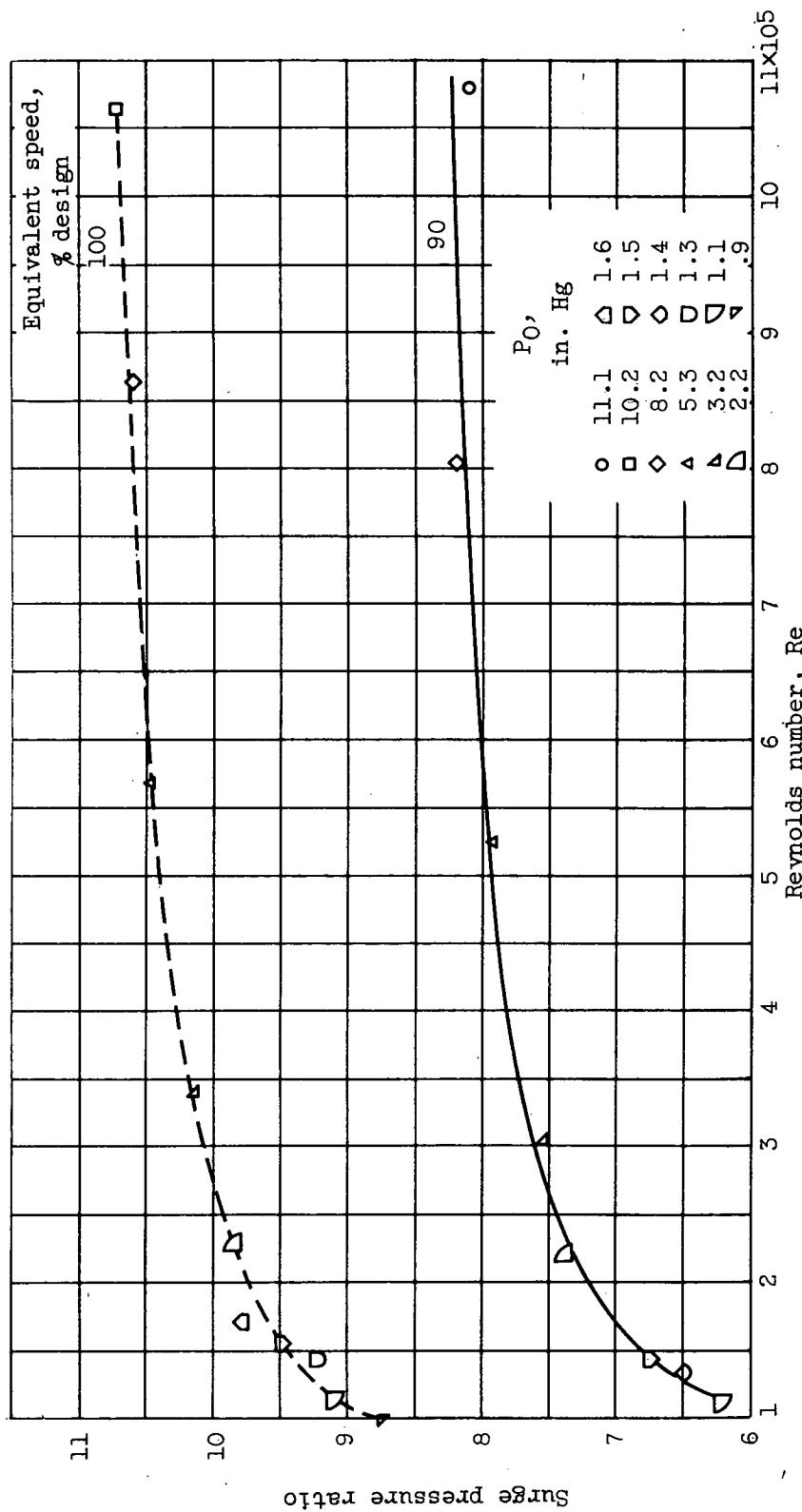
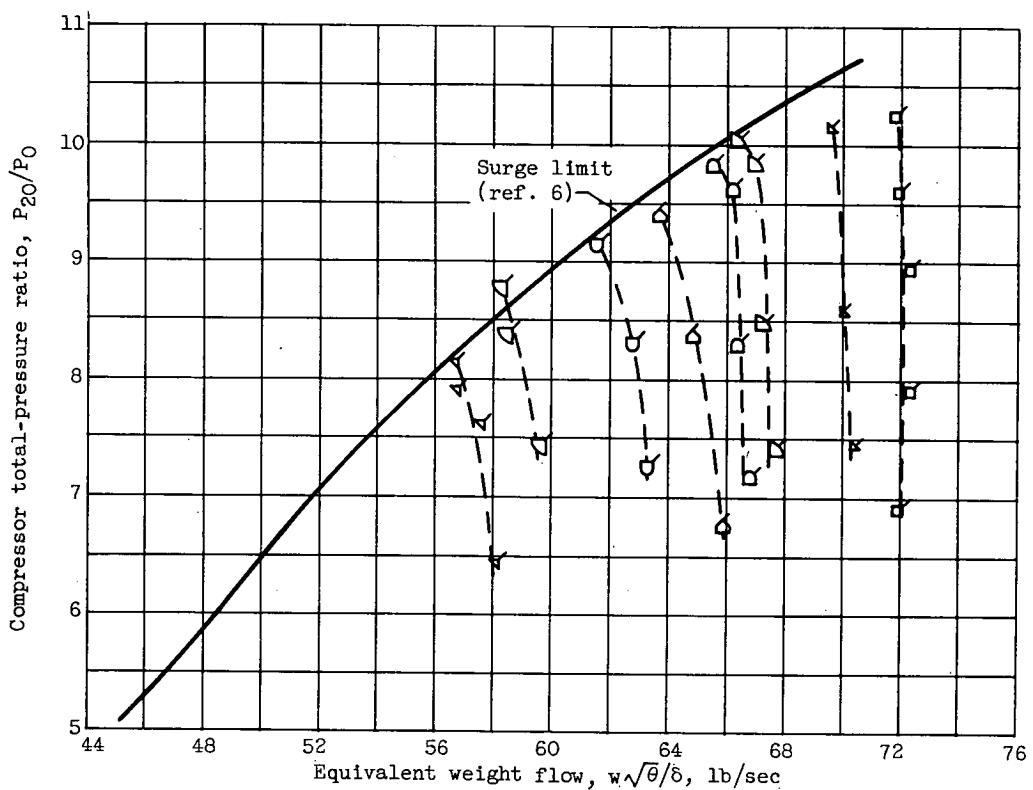
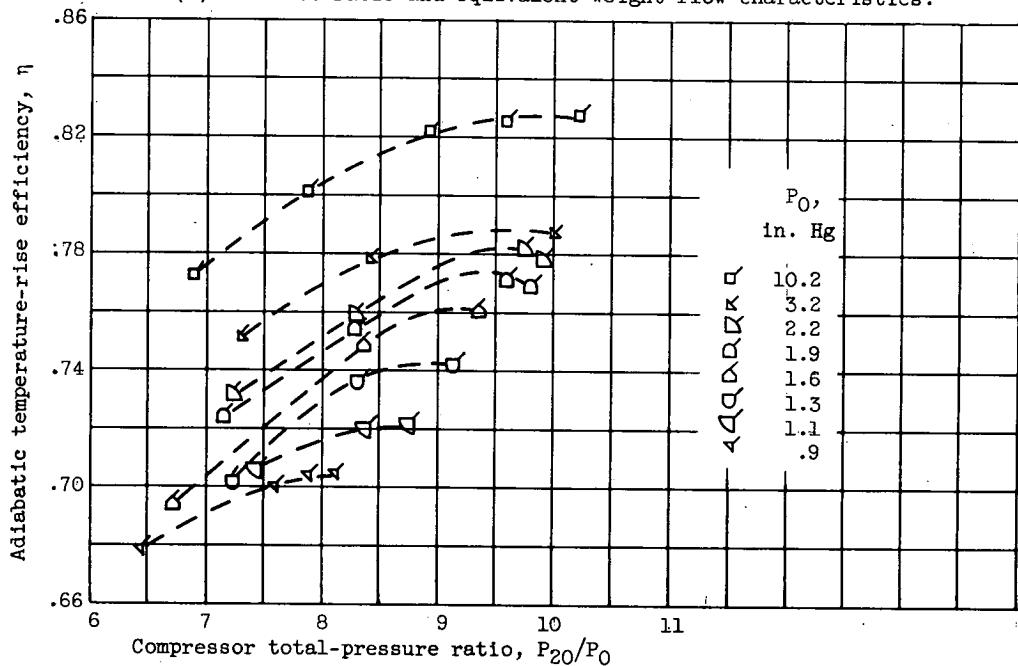


Figure 7. - Variation of surge pressure ratio with Reynolds number. Inlet temperature, $410^\circ R$; compressor uninsulated.

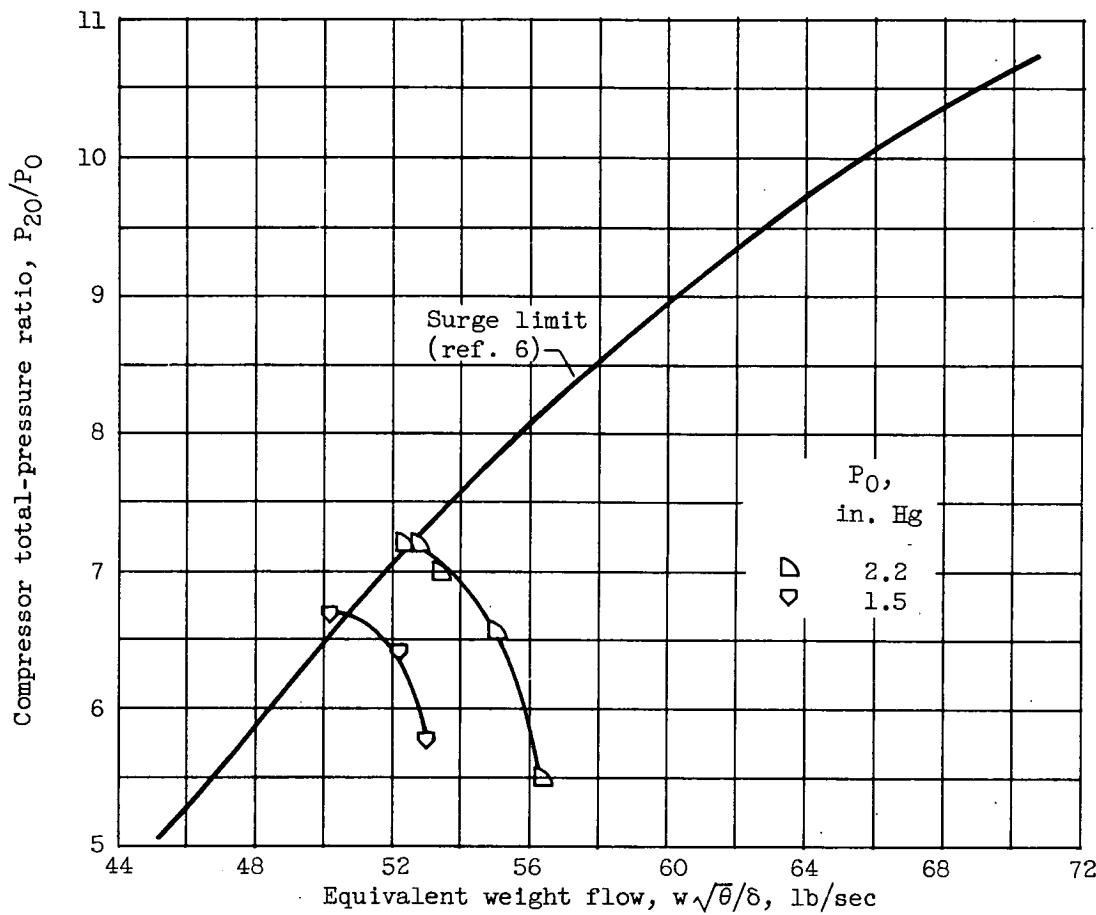


(a) Pressure-ratio and equivalent-weight-flow characteristics.

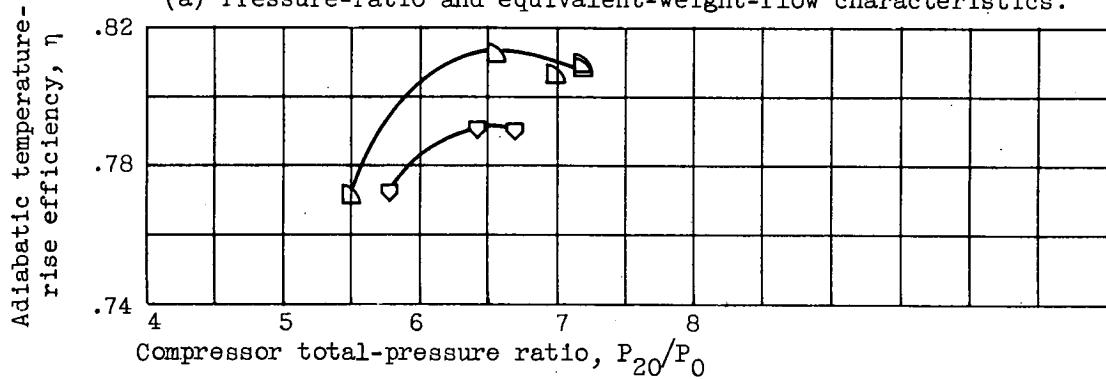


(b) Efficiency and pressure-ratio characteristics.

Figure 8. - Effect of inlet pressure on over-all performance. Inlet temperature, 410° R; compressor insulated; equivalent speed, 100-percent design.

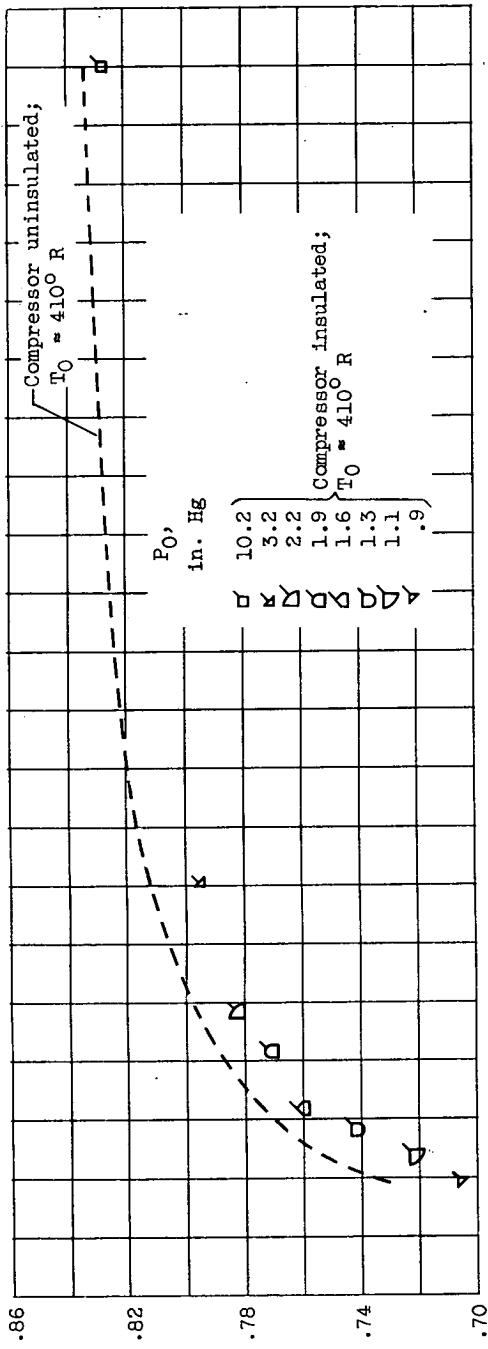


(a) Pressure-ratio and equivalent-weight-flow characteristics.

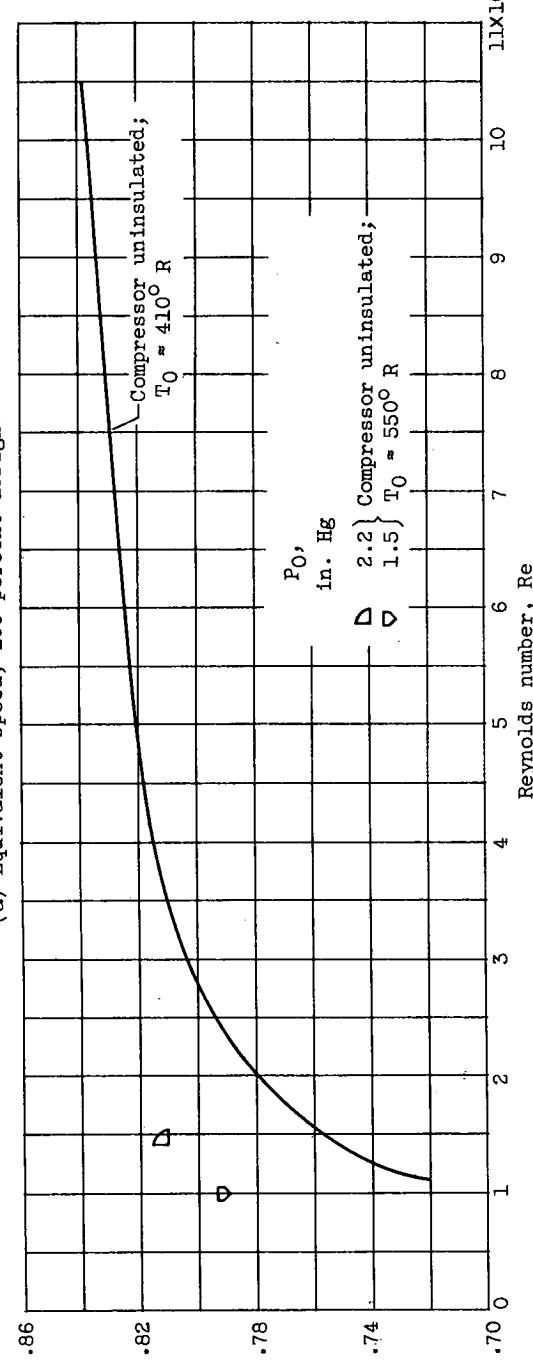


(b) Efficiency and pressure-ratio characteristics.

Figure 9. - Effect of inlet pressure on over-all performance. Inlet temperature, 550° R; compressor uninsulated; equivalent speed, 90-percent design.



(a) Equivalent speed, 100-percent design.



(b) Equivalent speed, 90-percent design.

Figure 10. - Variation of peak efficiency with Reynolds number.

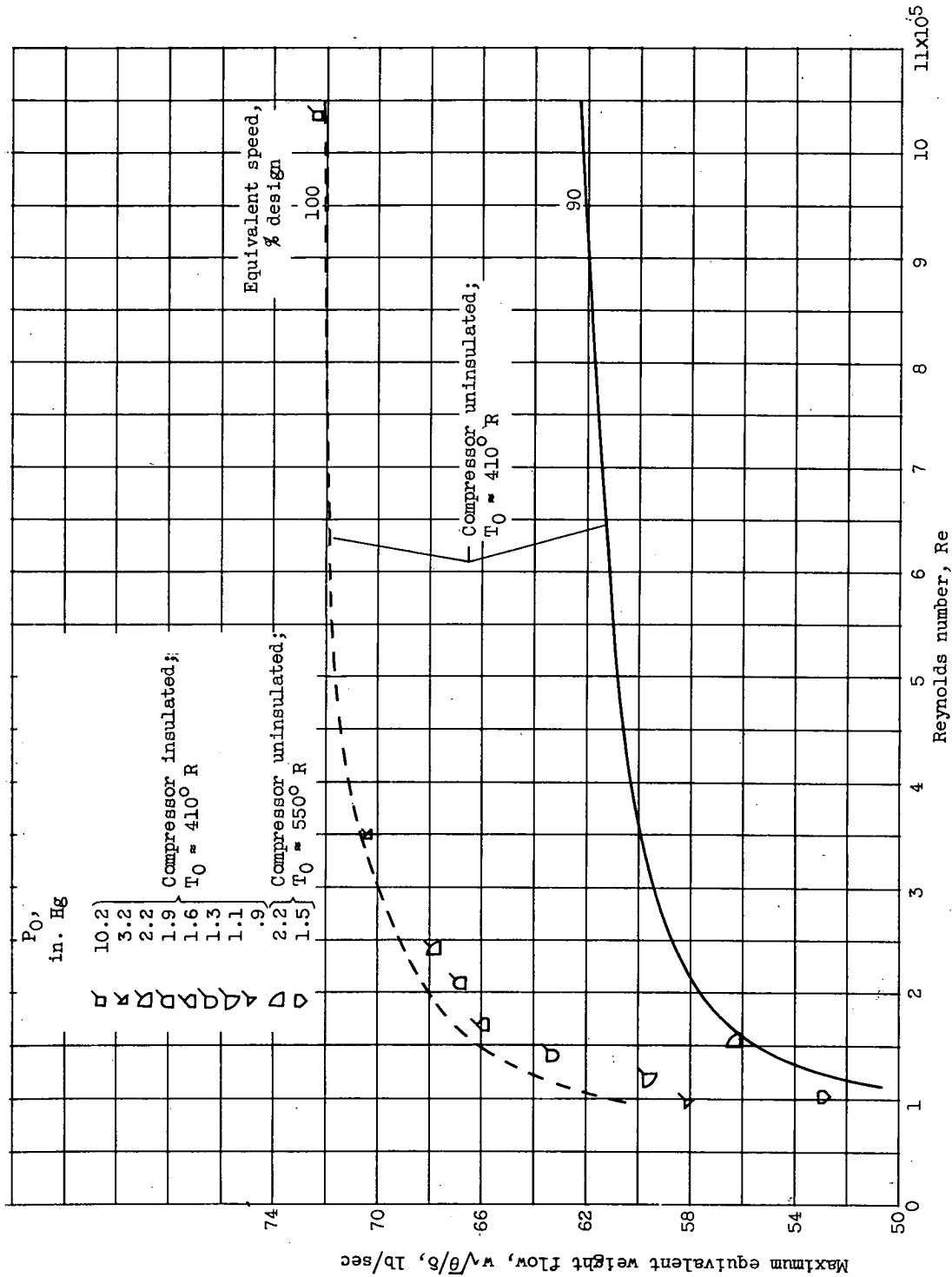


Figure 11. - Variation of maximum equivalent weight flow with Reynolds number.

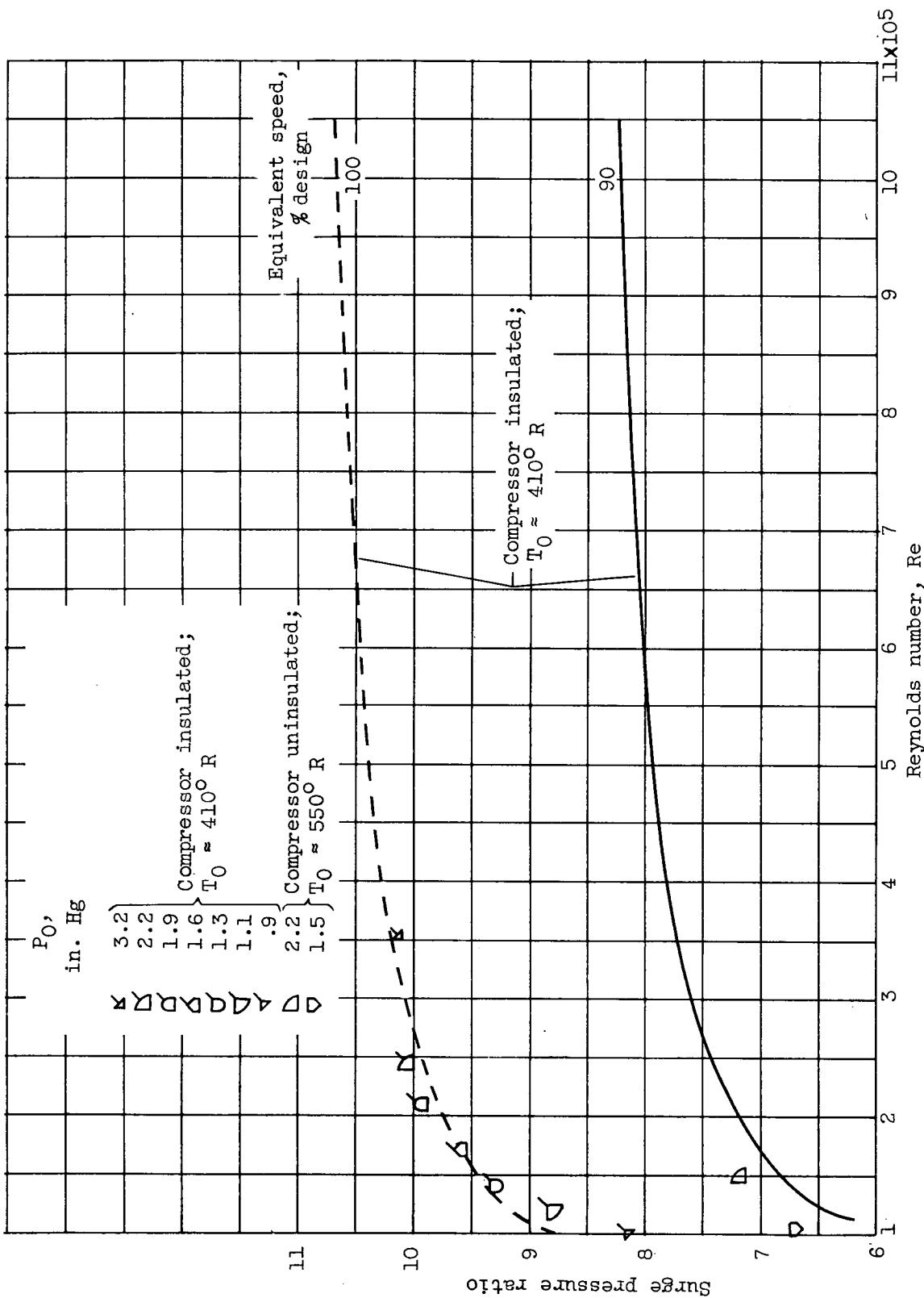


Figure 12. - Variation of surge pressure ratio with Reynolds number.